

In-space Manufacturing: Pioneering a Sustainable Path to Mars

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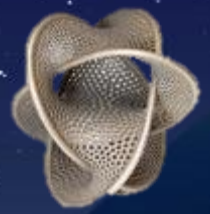
What is In-space Manufacturing (ISM)?

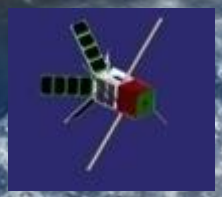
- ISM is responsible for developing the manufacturing capabilities that will provide on-demand, sustainable operations during NASA Exploration Missions (in-transit and on-surface). This includes testing & advancing the desired technologies, as well as establishing the required skills & processes for the processes (such as certification and characterization) that will enable the technologies to become institutionalized.
- These technologies are evolving quickly. ISM leverages industry, academia, & other govt. organizations to meet these objectives.
- ISM utilizes ground-based and International Space Station (ISS) demonstrations as the proving ground for the evolution of these capabilities from earth-reliant to earth-independent.

TECHNOLOGIES










+

SKILLS & PROCESSES

Design Optimize



Characterize



Certify



=

On-demand Manufacturing Capability for Exploration Missions

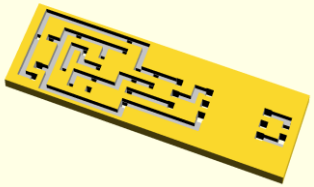
More than just 3D Printing….
In-space Manufacturing Technology Development Areas

RECYCLER



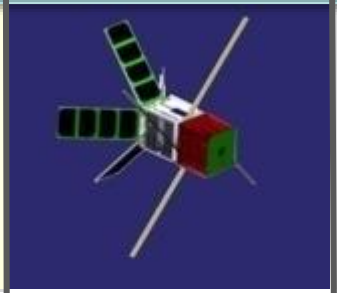
Recycling/Reclaiming 3D Printed Parts and/or packing materials into feedstock materials. This capability is crucial to sustainability in-space.

PRINTED ELECTRONICS



Leverage ground-based developments to enable in-space manufacturing of functional electronic components, sensors, and circuits.
Image: *Courtesy of Dr. Jessica Koehne (NASA/ARC)*

PRINTABLE SATELLITES



The combination of 3D Print coupled with Printable Electronics enables on-orbit capability to produce “on demand” satellites.

MULTI MATERIAL 3D PRINTING



Additively manufacturing metallic parts in space is a desirable capability for large structures, high strength requirement components (greater than nonmetallics or composites can offer), and repairs. NASA is evaluating various technologies for such applications. Image: *Manufacturing Establishment website*

EXTERNAL STRUCTURES & REPAIRS



Astronauts will perform repairs on tools, components, and structures in space using structured light scanning to create digital model of damage and AM technologies such as 3D Print and metallic manufacturing technologies (e.g. E-beam welding, ultrasonic welding, EBF3) to perform the repair. Image: *NASA*

ADDITIVE CONSTRUCTION



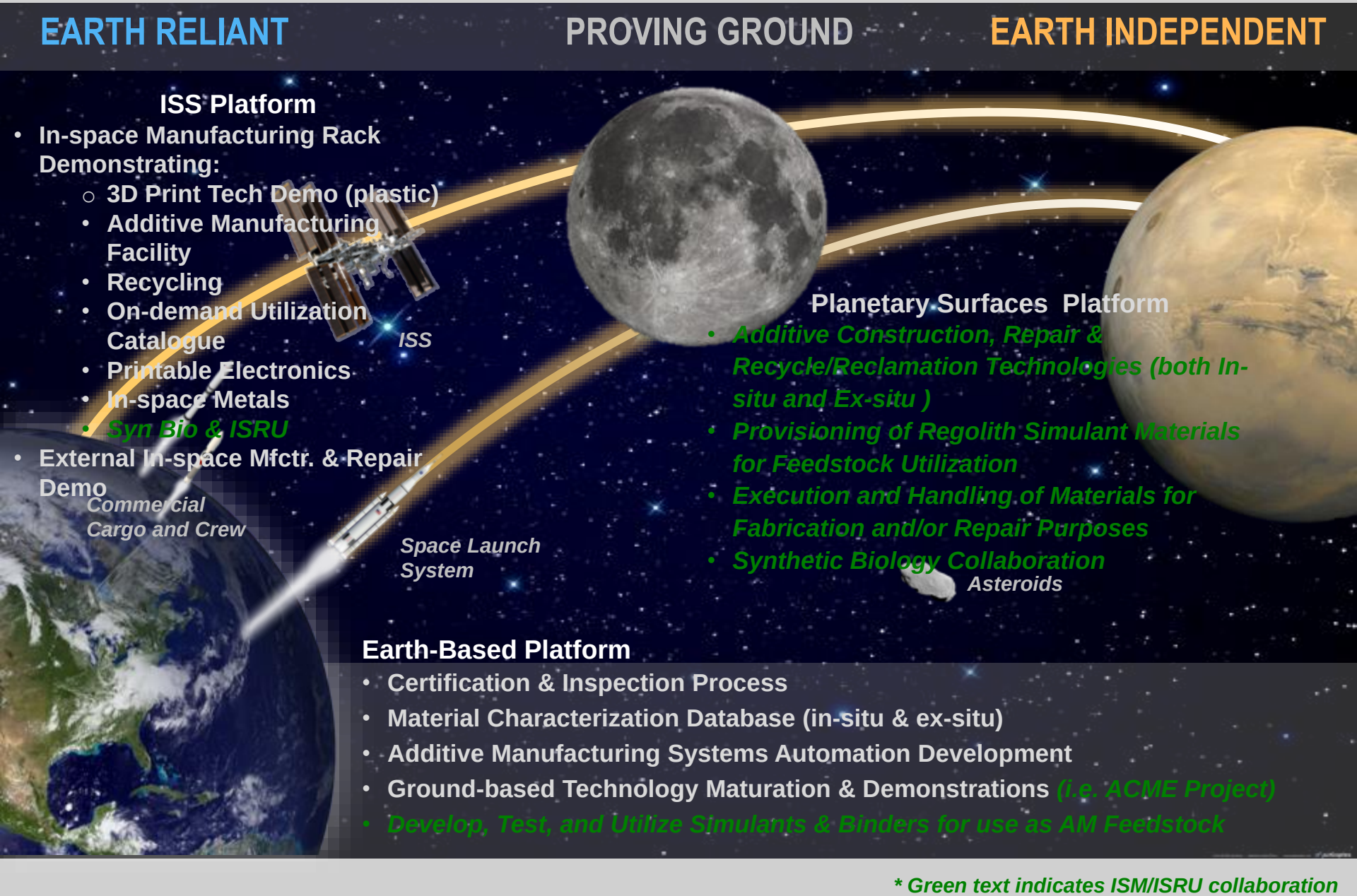
Contour Crafting Simulation Plan for Lunar Settlement Infrastructure Build-Up
B. Khoshnevis, USC



Illustration of a lunar habitat, constructed using the Moon's soil and a 3D printer.
Credit: Foster+Partners

ISM Technologies Under Development for Sustainable Exploration Missions

In-space Manufacturing (ISM) Path to Exploration



** Green text indicates ISM/ISRU collaboration*

In-space Manufacturing Phased Technology Development Roadmap

Earth-based





Pre-2012

Ground & Parabolic centric:

- Multiple FDM Zero-G parabolic flights
- Trade/System Studies for Metals
- Ground-based Printable Electronics/Spacecraft
- Verification & Certification Processes under development
- Materials Database
- Cubesat Design & Development

Demos: Ground & ISS



3D Print Tech Demo



Plastic Printing Demo

Add Mfctr. Facility

Recycler

Printable Electronics

Metal Printing

SmallSats

Self-repair/ replicate

External In-space Mfctr

2014

- **In-space:3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **AF/NASA Space-based Additive NRC Study**
- **ISRU Phase II SBIRs**
- **Ionic Liquids**
- **Printable Electronics**

2015 2016

- ***3D Print Demo***
- ***Future Engineer Challenge***
- ***Utilization Catalogue***
- ***ISM Cert Process***
- ***Add. Mfctr. Facility (AMF)***
- ***In-space Recycler SBIR***
- ***In-space Material Database***
- ***External In-space 3D Printing***
- ***Autonomous Processes***
- ***ACME Simulant Dev. & Test for Feedstock; Ground Demo***

2017 2018

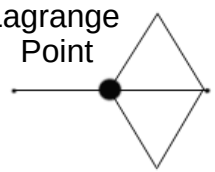
ISS: *Utilization/Facility Focus*

- In-space Recycler Demo
- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Printable Electronics Tech Demo
- Synthetic Biology Demo
- Metal Demo Options
- ***ACME Ground Demos***

Exploration



Asteroids



Lagrange Point



Lunar



Mars

2020-25

Lunar, Lagrange FabLabs

- Initial Robotic/Remote Missions
- ***Provision feedstock***
- ***Evolve to utilizing in situ materials (natural resources, synthetic biology)***
- ***Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. "living off the land"***
- Autonomous final milling to

2025

Planetary Surfaces Points Fab

- Transport vehicle and sites would need Fab capability
- ***Additive Construction & Repair of large structures***

2030 - 40

Mars Multi-Material Fab Lab

- ***Provision & Utilize in situ resources for feedstock***
- ***FabLab: Provides on-demand manufacturing of structures, electronics, & parts utilizing in-situ and ex-situ (renewable) resources.*** Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment at remote destinations.

ISS Serves as a Key Exploration Test-bed for the Required Technology Maturation & Demonstrations

**** Green text indicates ISM/ISRU collaboration***

ISM Step #1: First 3D Printer in Space!





- The 3D Print Tech Demo launched on SpaceX-4 (9/21/14) and was installed in the Microgravity Science Glovebox on ISS. The printer was designed and built by Made in Space, Inc. under NASA Small Business Innovation Research contract.
- To date, 21 parts have been printed in space (13 unique designs); the printer functioned nominally.
- First part “emailed” to Space: 3D Print of a ratchet tool demonstrated on-demand capability by uplinking a part file that was not pre-loaded to the 3D Printer.
- The first flight samples were ‘unboxed’ at NASA MSFC in April 2015. Test & Analyses is underway with results to be openly published Fall 2015



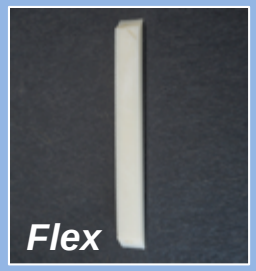
Images courtesy of NASA

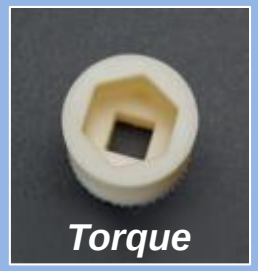
3D Printer International Space Station (ISS) Technology Demonstration Initial Samples

Mechanical Property Test Articles











Functional Tools









Printer Performance Capability











In-Space Manufacturing Tasks

◆ Material Characterization Database Development

- Objective: Characterize microgravity effects on printed parts and resulting mechanical properties Develop design-level database for microgravity applications.
- MSFC team has performed initial characterization on ABS and ULTEM.
- B-basis dataset received from RP+M for ULTEM through America Makes project
- MSFC will generate design property database from ground samples produced using the flight spare 3D printer.
- Phase II operations for additional on-orbit prints of engineering test articles are being planned with ISS for later this year.
- All datasets will be available through the MSFC Materials and Processes Technical Information System (MAPTIS)

◆ On-demand ISM Utilization Catalogue Development

- Objective: Develop a catalogue of approved parts for in-space manufacturing and utilization.
- Joint effort between MSFC AM materials and process experts and space system designers and JSC ISS Crew Tools Office
- Parts being considered include crew tools, payload components, medical tools, exercise equipment replacement parts, cubesat components, etc.
- First parts are in design and ground test process.



ISM Characterization of Materials and Process Variability (above)



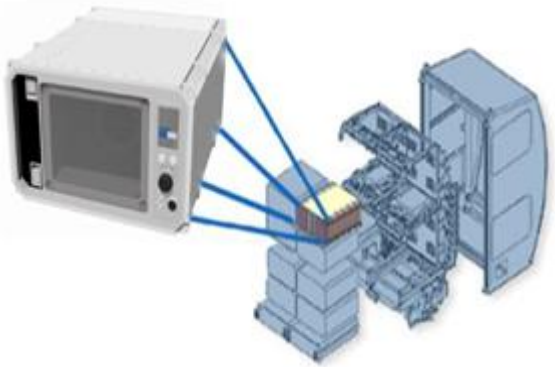
Housekeeping Vacuum Crevice Tool



EVA Suit Fan Shipping Container: Design Clearances had to be relaxed for part to be printed on one FDM printer (red) vs. another in order for the parts to be assembled.

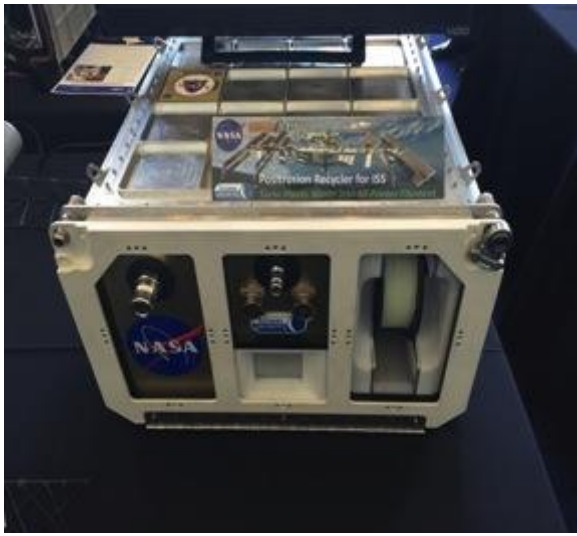
In Space Manufacturing Tasks

- **AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space, Inc.**
 - Commercial printer for use on ISS
 - Incorporates lessons learned from 3D Printer ISS Tech Demo
 - Expanded materials capabilities: ABS, ULTEM, PEEK
 - Increased build volume
 - Anticipated launch late CY2015



Additive Manufacturing Facility (AMF)

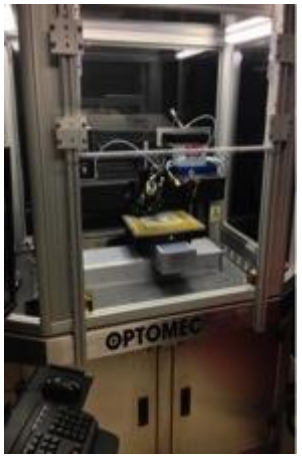
- **In-space Recycler ISS Technology Demonstration Development (SBIR 2014)**
 - Objective: Recycle 3D printed parts into feedstock to help close logistics loop.
 - Phase I recycler developments completed by Made In Space and Tethers Unlimited.
 - Phase II SBIR (2014) awarded to Tethers Unlimited.
 - Final deliverable will result in flight hardware for the In-space Recycler for proposed ISS Technology Demonstration in FY2017.
- **Launch Packaging Recycling Phase I SBIR (2015)**
 - Objective: Recycle launch packaging materials into feedstock to help close logistics loop



Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo

In-Space Manufacturing Tasks

- **In-space Printable Electronics Technology Development**
 - Development of inks, multi-materials deposition equipment, and processes
 - Collaborating with Xerox Palo Alto Research Center (PARC) on Printable Electronics technologies developed at MSFC and Xerox PARC.
 - NASA Ames Research Center developing plasma jet printable electronics capability
 - Jet Propulsion Lab (JPL) has Advanced Concepts project to develop “printable spacecraft”
 - Printable Electronics Roadmap developed targeting ISS technology demonstrations including RF sensors/antennae, in-space printed solar panel, and printable cubesats
- **In-space Multi-Material Manufacturing Technology Development**
 - In-space Adaptive Manufacturing (ISAM) project with Dynetics utilizing the Hyperbaric Pressure Laser Chemical Vapor Deposition (HP-LCVD)
 - HP-LCVD technology holds promise for a novel solution to manufacturing with multiple materials (including metallics) in microgravity.
 - Phase I deliverable is spring similar to design utilized on ISS

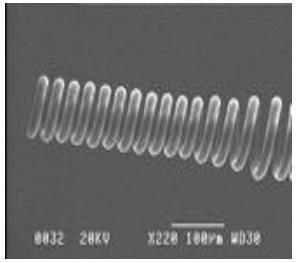






Printable Electronic Technologies

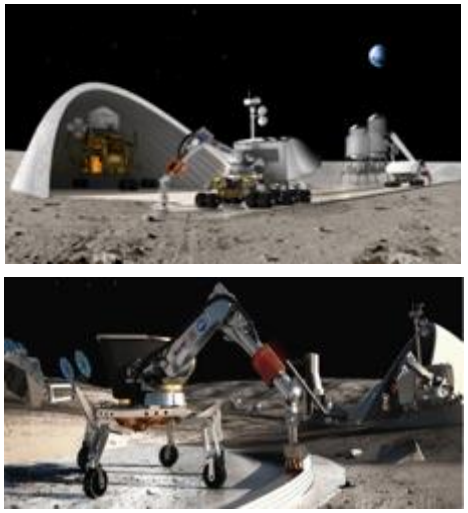




Spring Created by Adaptive Manufacturing

In Space Manufacturing Collaborations

- **ACME - Additive Construction by Mobile Emplacement (NASA STMD GCD & Army Corps of Engineers)**
 - Joint initiative with the U. S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) Automated Construction of Expeditionary Structures (ACES) Project
 - Objective: Develop a capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials and minimum number of personnel.
 - Goal: Produce half- scale and full-scale structures with integrated additive construction system at a lab or planetary analog site (September 2017)



Additive construction Concept on extraterrestrial surface. Courtesy: B. Khoshnevis, CCC

- **NASA/DARPA External In-space Manufacturing & Repair BAA (To be released in FY16)**
 - Objective: External Additive Manufacturing shows great promise for Exploration missions. A joint NASA/ Defense Advanced Research Projects Agency (DARPA) Broad Agency Announcement (BAA) is proposed to explore the technologies available today that could be utilized for a future in-space demonstration.
 - Targeted Areas of Interest for an External In-space Manufacturing & Repair Technology Flight Demo include: Additive Manufacturing Technologies, Printable Electronics, Autonomous & Remote Ops, Inspection - Manufacturing context, situational awareness and metrology, Ionic Liquids Extraction & Utilization

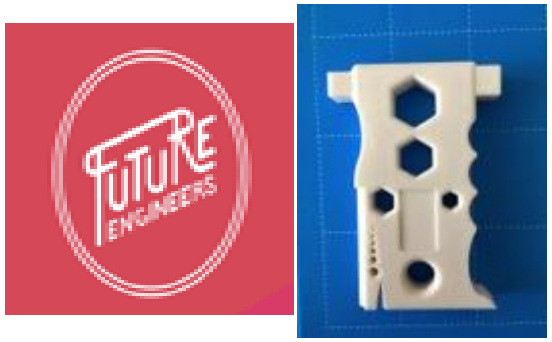


External In-space Manufacturing & Repair Technologies

In-space Manufacturing STEM & Outreach: Leveraging External Platforms for Technology and Skillset Development

National Future Engineers STEM Program*:* National challenge conducted jointly by NASA and American Society of Mechanical Engineers (ASME)

- Competition was held in two divisions, Junior (K-12) and Teen (13-18)
- First Challenge was to design a tool that astronauts could use on ISS. Teen winner's part will be printed on ISS later this year.
- The Space Container Challenge was announced on 5/12/15 and closes 8/2/15. www.futureengineers.org
- Discussions underway for a joint NASA/IndyCar Challenge



Future Engineers Winning Part – Multi-purpose Maintenance Tool (MPMT)

NASA GrabCAD Handrail Clamp Assembly Challenge

- GrabCAD has a community of nearly 2 million designers
- Challenge was to design a 3D Printed version of the Handrail Clamp Assembly commonly used on ISS
- Nearly 500 entries in three weeks
- Five winners were selected



ISS Handrail Clamp Assembly GrabCAD (left) & traditional (right)



In-space Manufacturing Initiative Summary

In order to provide meaningful impacts to Exploration Technology needs, the ISM Initiative Must Influence Exploration Systems Design Now.

- **In-space Manufacturing offers:**
 - Dramatic paradigm shift in the development and creation of space architectures
 - Efficiency gain and risk reduction for low Earth orbit and deep space exploration
 - "Pioneering" approach to maintenance, repair, and logistics will lead to sustainable, affordable supply chain model.
- **In order to develop application-based capabilities in time to support NASA budget and schedule, ISM must be able to leverage the significant commercial developments.**
 - Requires innovative, agile collaborative mechanisms (contracts, challenges, SBIR's, etc.)
 - NASA-unique Investments to focus primarily on adapting the technologies & processes to the microgravity environment.
- **We must do the foundational work – it is the critical path for taking these technologies from lab curiosities to institutionalized capabilities.**
 - Characterize, Certify, Institutionalize, Design for AM
- **Ideally, ISS US Lab rack or partial rack space should be identified for In-space Manufacturing utilization in order to continue technology development of a suite of capabilities required for exploration missions, as well as commercialization on ISS.**



BACKUP

ISM WBS


NASA Technical Authority
Chief Engineer
Chief Safety Officer
1.0 In-Space Manufacturing
Project Management
Resource Analyst
1.1 In-space Manufacturing Technologies
3D Printing in Zero-G Tech Demo
Additive Manufacturing Facility (AMF)
In-space Recycling Capability
Printable Electronics
In-Space Metals Printing
Autonomous and Remote Operation Technologies
1.2 Materials Characterization
Material Properties Needed for Design using FDM
Develop Material Properties Database
Develop Design & Analyses Tools & Models
Quantification of Variables Affecting Baseline Database
- Microgravity
- Printer Capability
- Feedstock
- Recycler Process
1.3 Parts Utilization Catalogue
Catalogue Content Definition
Develop Catalogue Database Format and Structure
Develop Process for Candidate Part Inclusion
- Sample Part Dev
- Verification & Validation Process Dev
1.4 In-Space External Manufacturing & Repair
External In-space Additive Manufacturing and Repair Technology Development
DARPA/NASA BAA
1.5 STEM Outreach
Future Engineers Challenges
GRAB CAD Challenge

ISM Level – 1-4 Requirements Decomposition

Level 1
HQ - Level 1 Objective

Level 2
AES, STMD and ISS Program - Level 2 Requirements

Level 3
In-Space Manufacturing (Former 3D Print) Project - Level 3 Requirements

Level 4
Level 4 Requirements - Made In Space Contract and In-house Task

New Expanded Requirements for In-Space Manufacturing in Addition to Original 3D Print Above

Utilize ISS as a Test Bed to further TRL maturation on enabling and critically enhancing technologies needed for long duration human exploration beyond earth orbit

OCT Materials, Structures, Mechanical Systems, & Manufacturing Road Map, Technology Area 12
- Table 18 Page TA12-22,"d.in-space assemby, fabrication and repair introduction of new materials and methods to fabricate structures in-sapce"
-Sec 5.2.1 para 6 p TAI2-31, "Enable cost-effective manufacturing for reliable high performance structures and mechanisms made in low-unit production, including in space manufacturing"
-Sect 5.3 12.4.2 Intellegent Integrated Manufacturing and Cyber Physical Systems (Manufacturing) p TA12-33, "This technology would enable physical components to be manufactured in space, on long-duration human missions if necessary.

NASA Human Research Program (HRP) Decadal Survey AP10
- Design and Devolop advanced materials tha tmeet new property requirements to enable human exploration at reduced cost using both current and novel materials synthesis and processing techniques and computational methods.

In-Space Manufacturing shall develop a parts cataloge of pre approved items that can be printed in-space to support ISS and Exploration needs.

In-Space Manufacturing shall develop production In Space Manufacturing capability to support ISS & Future Exploration Needs.

In-Space Manufacturing shall develop a STEM outreach program to gather interest from the public

The In-Space Manufacturing Project shall develop and institutionalize a Verification and Certification Process for candidate parts to be included in the parts catalogue that ensures that the part designs meet all functional and ISS interface / safety requirements.

The In-Space Manufacturing Project shall develop a process for identifying candidate parts for addition to parts cataloge database

The In-Space Manufacturing Project shall develop an electronic database cataloge of pre approved items parts that can be called up and printed on an as needed basis

The In-Space Manufacturing Project shall develop a Material Characterization Database that quantifies the material properties of print material in the as printed state such as needed by a design engineer to facilitate the design of parts in the parts cataloge

The In-Space Manufacturing Project shall develop NASA customer goals and requirements for an In-Space Manufacturing Facilities both for commercial, ISS and exploration applications.

The In-Space Manufacturing Project shall develop a design capability for Additive Manufacturing that takes advantage of the microgravity and exoplanetary environments.

In-Space Manufacturing Project shall develop printable electronics ground demo to enable additive manufacturing of electronic circuits for in space applications.

The In-Space Manufacturing Project shall develop an ISS in space recycler tech demo development to enable use of available materials and minimize launch of renewable resources.

The In-Space Manufacturing Project shall develop a quality assessment approach to assure that the parts printed are manufactured to the design requirements intended.

The In-Space Manufacturing Project shall develop technology to enable automated remote in space additive manufacturing for ISS and explorations applications.

The In-Space Manufacturing Project shall develop technology to enable large scale structure manufacturing in the exposed vacuum environment of space.

The In-Space Manufacturing Project shall develop technology to enable additive repair of tools, components and structures in space to cut dependence on earth to orbit replacement of damaged parts.

The In-Space Manufacturing Project shall develop a Future Engineers Program 3D printing in space challenge to design a tool that could be used in space including students in grades K-12.

The In-Space Manufacturing Project shall utilize MAPTIS to publish results for the material database

The In-Space Manufacturing Project shall ensure that the lessons learned from the 3D Print Technology Demonstration are integrated into the AMF printer and will be applicable to NASA ISM objectives.

The In-Space Manufacturing Project shall develop and implement a procurement model for NASA to procure print services from the MIS AMF commercial 3D Printer on ISS.

Automation & Sensor Development for Remote operation of Additive Manufacturing Technologies

External In-space Manufacturing BAA

3D Printing ISS Tech Demo Sample Testing Techniques

Visual and photographic Inspection

- Identification and documentation of anomalies, damage (e.g., print tray removal damage)
- Identification and documentation of any visual differences between flight and ground samples (initial identification of microgravity effects)
- Attention will be given to any signs of delamination between layers, curling of the sample, surface quality, damage, voids or pores, and any other visually noticeable defect.



Visual Inspection of Flight and Ground Parts

Mass Measurement / Density Calculation

- Mass measurement using a calibrated laboratory scale accurate to 0.1mg repeated five times for a mean mass
- Density calculation requires the volume determined by structured light scanning
 - Provides information on void space or expansion of the material created during the printing process
 - Flight samples will be compared with their respective ground samples to assess any differences



Laboratory Scales utilized for Mass & Density Calculations

3D Printing ISS Tech Demo Sample Testing Techniques

Structured Light Scanning

- ATOS Compact Scan Structured Light Scanner
- Blue light grid projected on the surface
- Stereo-images captured
- Image processing provides
 - A CAD model of the printed part
 - A comparison of the printed part and the original CAD file from which the part was printed
 - A statistically valid determination of the volume of the sample



ATOS Compact Scan Structured Light Scanner

Computed Tomography (CT) Scanning/X-Ray

- Phoenix Nanome|x 160
- X-ray scans
- Provides 2D and 3D models of the internal structures that could affect mechanical properties
 - Internal voids
 - De-lamination of the ABS layers
- Resolution as low as 8-10 microns is possible

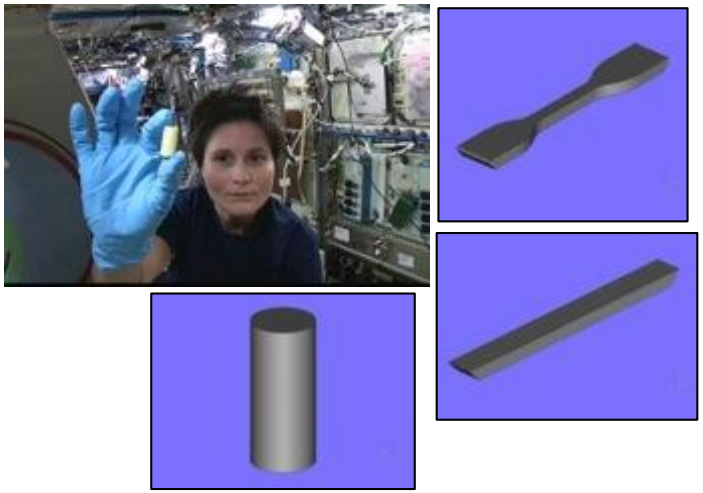


Phoenix Nanomelx 160 CT Scan

3D Printing ISS Tech Demo Sample Testing Techniques

Mechanical (Destructive) Testing

- ASTM Standards Applied on Mechanical Samples only
- D638 for tensile testing
 - Tensile strength, tensile modulus, and fracture elongation
- D790 for flexure testing
 - Flexural stress and flexural modulus
- D695 for compression testing
 - Compressive stress and compressive modulus



Mechanical Samples for Destructive Testing

Optical and Scanning Electron Microscopy

- Detail the surface microstructures of the layers
- Detail the surface of the flight prints damaged by over-adhesion to the build tray; it is hoped this will identify the root cause of seemingly increased adhesion of part to tray
- Inter-laminar regions will be investigated; flight and ground samples will be compared
- Defects or anomalies noted by the initial inspection will examined, as well as the fracture surfaces from the mechanical tests



Leica M205-A Optical Microscope



Hitachi S-3700N Scanning Electron Microscope